NOAA TECHNICAL MEMORANDUM NWS CR-107

FLOOD FORECASTING FOR THE LOWER MISSOURI RIVER BASIN: JUNE - SEPTEMBER, 1993

John F. Pescatore
Missouri Basin River Forecast Center
Pleasant Hill, Missouri

September 1994

U.S DEPARTMENT OF Commerce / National Oceanic and Atmospheric Administration / National Weather Service

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UNITED STATES DEPARTMENT OF COMMERCE
Ronald H. Brown
Secretary

National Oceanic and Atmospheric Administration
D. James Baker
Under Secretary

National Weather Service
Elbert W. Friday, Jr.
Assistant Administrator

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FLOOD FORECASTING FOR THE LOWER MISSOURI RIVER BASIN: JUNE - SEPTEMBER, 1993

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1. INTRODUCTION

The National Weather Service (NWS) is the largest component of the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA). The mission of the NOAA/NWS Hydrologic Services program is to provide:

(a) River and flood forecasts and warnings for protection of life and property and . . .

(b) Basic hydrologic forecast information for the Nation's economic and environmental well-being.

Thirteen River Forecast Centers, located throughout the United States (Figure 1) provide a variety of hydrologic products that include water supply outlooks, spring flood outlooks, flash flood guidance, flood forecasts, reservoir inflow forecasts and general river forecasts for navigation and recreation.

The Missouri Basin River Forecast Center (MBRFC) was established in October of 1946. From its present location in Pleasant Hill, Missouri, the MBRFC provides a variety of hydrologic services within its 530,000 square mile area of responsibility. The Missouri River Basin is meteorological and hydrologically diverse; the area comprises some or all of ten states and a portion of southern Canada (Figure 2).

The Missouri Basin RFC coordinates its hydrologic forecasting efforts with the U.S. Army Corps of Engineers (COE), U.S. Geological Survey (USGS), Soil Conservation Service (SCS), U.S. Bureau of Reclamation, other NWS RFCs and NWS Forecast Offices (WSFOs). Without the frequent exchange of information between these offices, the Missouri Basin RFC could not fulfill its duties.

2. GENERAL

The 1993 Midwest Floods were the consequence of hydrological and climatological anomalies. The Midwestern United States received above normal precipitation for the last six months of 1992. This trend continued into 1993, and by early spring, agricultural interests were affected as seed planting was delayed because of saturated soils.

[1]Current affiliation: WSO Morristown, Tennessee.

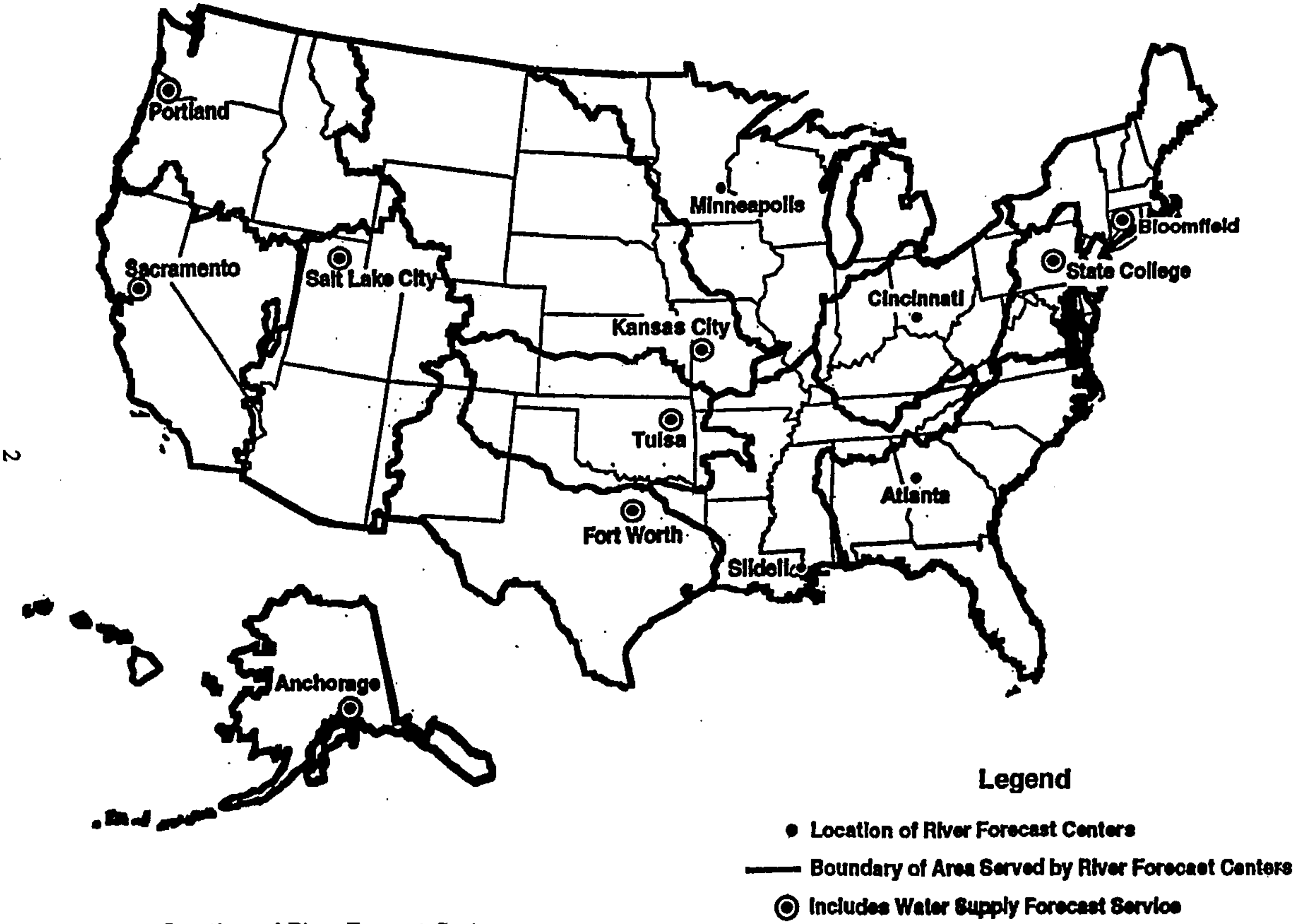
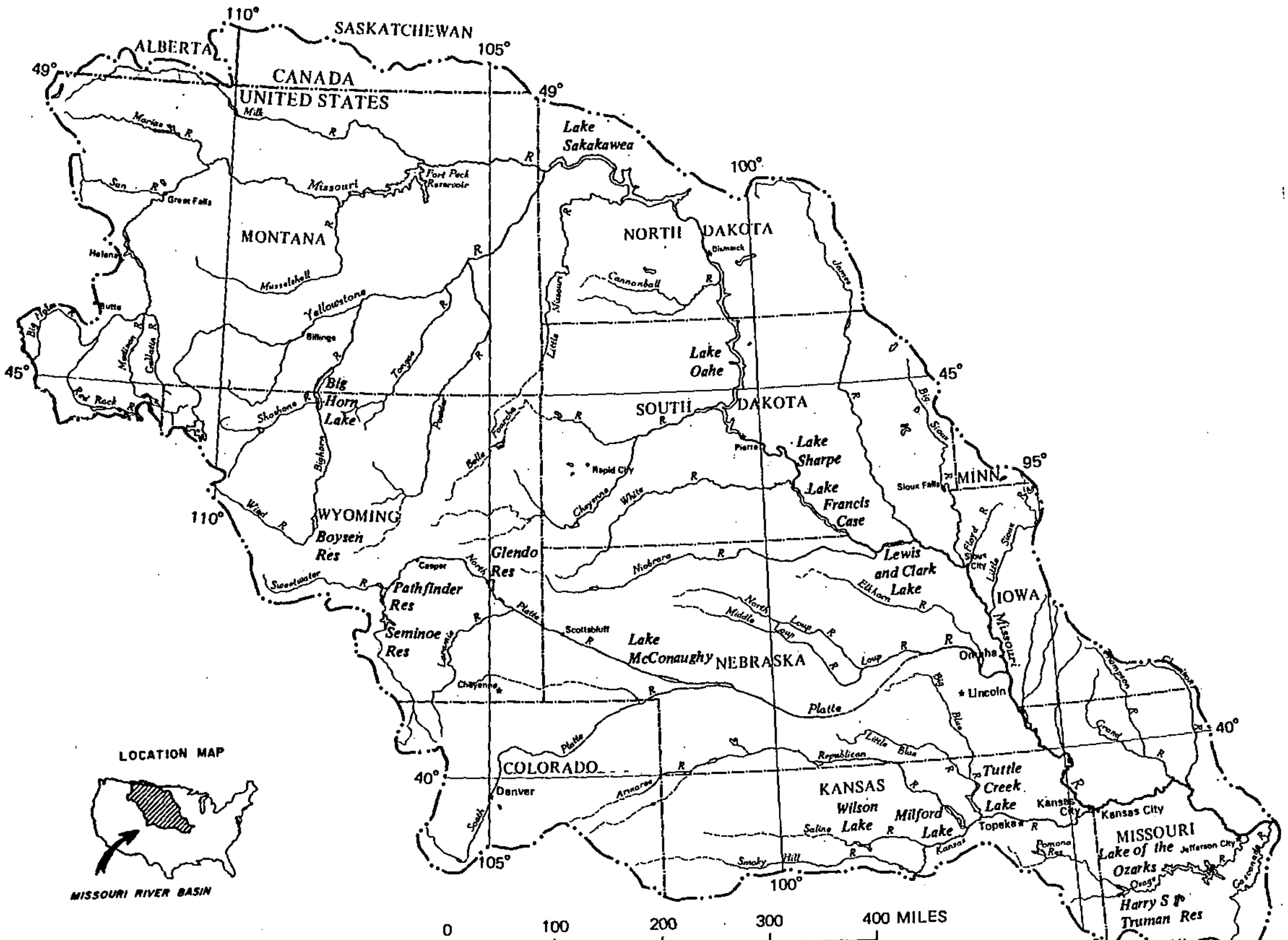


Figure 1. Locations of River Forecast Centers.



Base from U.S. Geological Survey,
United States base map

Figure 2. Missouri River Basin.

Relentless precipitation during the spring and summer drenched the Midwest and caused major flooding of rivers and streams. Floodwater breached levees, inundated farmland, damaged homes and businesses, and disrupted rail and surface transportation. Railroads were especially hard-hit by flooding as approximately 500 miles of track were underwater on more than one occasion. Forty-eight flood-related deaths were reported, and property damages are estimated at 15 to 20 billion dollars for the nine affected midwestern states.

3. SYNOPTIC WEATHER PATTERN

During late spring and summer of 1993, the jet stream which typically flows across southern Canada, veered southward over the central Rockies and then across the upper Midwest with a southwest to northeast orientation.

An unusually strong ridge of high pressure, situated over the eastern United States, existed in contrast to a trough of low pressure over the northwestern United States. A frontal boundary associated with the quasi-stationary jet stream allowed for overrunning of the cooler, drier air to the north by the warmer, moist air from the south. Circulation patterns from these contrasting areas on either side of the jet stream enhanced the south to north transport of moisture by advection.

Shortwave troughs moving out of the Rockies would cause disturbances to propagate along the surface front setting off frequent, often spectacular thunderstorms over the central United States.

4. RECORD PRECIPITATION AND RECORD STAGES

State precipitation rankings from the National Climatic Data Center (NCDC), Asheville, North Carolina, show that Iowa and North and South Dakota reported their wettest July on record in 1993; Missouri and Nebraska had the third wettest July on record; Minnesota, Illinois and Kansas reported their second wettest July. For these states, average precipitation ranged from two to four times normal for the month of July. Certain regions of less areal extent indicated precipitation amounts much above four times July normals.

Unfortunately, much-above-normal July precipitation arrived on the heels of a wet spring-early summer period. By June, many rivers in Iowa, as well as the Missouri River below Gavins Point Dam were already flooding; most other rivers and streams were at least half-bankfull. July downpours not only exacerbated flooding conditions in the midwest, but also pushed reservoir pools and river stages to new record levels at many locations.

Runoff from July precipitation raised pools at several major reservoirs above spillway crest elevation. For example, the gated and uncontrolled spillways were used at Tuttle Creek Dam and Milford Dam respectively.

In July, record pool elevations were reached at Tuttle Creek, Milford, and Perry lakes in the Kansas River system; however, Clinton Reservoir, near Lawrence, Kansas, attained record pool elevation in May. The maximum combined releases at Milford, Tuttle Creek, and Perry dams reached approximately 100,000 cfs by late July. Floodwater poured over the spillway at Rathbun Lake in southern Iowa in July, marking the first time ever the emergency spillway was used.

In 1993, flooding along the Missouri River started in March. By early July, MBRFC flood forecast points along the Missouri River from Nebraska City, Nebraska, to the mouth were above flood stage and would remain so into September. Stages rose to new record levels at stations along the Missouri River from Plattsmouth, Nebraska to St. Charles, Missouri from late July to August 1 (Table 1).

TABLE 1
Missouri River
(Historical Floods Crest)

LOCATION	FLOOD STAGE	OFFICIAL FLOOD OF RECORD	UNOFFICIAL 1993 CREST
Missouri River			
Plattsmouth, MO	26.0	34.66 (6/14/84)	35.7 (7/25/93) River gage rose to 35.65 and stuck for about 24 hours.
Brownville, NE	32.0	41.2 (6/15/84)	44.3 (7/24/93)
St. Joseph, MO	17.0	26.8 (4/22/52)	32.69 (7/26/93)
Kansas City, MO	32.0	46.2 (7/14/51)	48.9 (7/28/93)
Napoleon, MO	17.0	26.8 (7/15/51)	27.76 (7/27/93)
Lexington, MO	22.0	33.3 (7/15/51)	33.4 (7/08/93)
Waverly, MO	20.0	29.2 (6/23/84)	31.2 (7/28/93)
Miami, MO	18.0	29.0 (7/16/51)	32.4 (7/29/93)
Glasgow, MO	25.0	36.7 (7/18/51)	39.6 (7/29/93)
Boonville, MO	21.0	3.28 (7/17/51)	37.1 (7/29 & 7/30/93)
Jefferson City	23.0	34.2 (7/18/51)	38.6 (7/30/93)
Gasconade, MO	22.0	38.7 (10/5/86)	39.6 (7/31/93)
Hermann, MO	21.0	35.8 (10/5/56)	36.3 (7/31/93)
St. Charles, MO	25.0	37.5 (10/7/86)	39.5 (8/01/93)
		(Near Flood of Record)	
Nebraska City, NE	18.0	27.7 (4/18/52)	27.16 (7/23/93)
Rulo, NE	17.0	25.6 (4/22/52)	25.24 (7/24/93)
Sibley, MO	22.0	35.6 (7/15/51)	34.6 (7/29/93)

5. FLOODING OF THE LOWER MISSOURI RIVER VALLEY FROM ST. JOSEPH, MISSOURI TO ST. CHARLES, MISSOURI

Major flooding of the mainstem of the Missouri River extended from below Gavin's Point Dam in South Dakota to the mouth; however, hydrologic modeling and forecasting difficulties were most prevalent from St. Joseph to St. Charles, Missouri. These lower reaches of the Missouri River that wind through the "Show-Me-State" will be specifically addressed later in the paper.

In 1993, the lower Missouri River, at one forecast point or another, was above flood stage every month since March. Three distinct events of rising hydrographs, namely July 10-16, July 26-August 1, and September 23-October 1 (Table 2) marked the 1993 flooding of the Missouri River. The episode of late July, which shattered historical records (and some records set earlier in the month), is given special emphasis in the next section.

TABLE 2

STATE OF MISSOURI
MISSOURI RIVER 1993 FLOOD CREST EPISODES

Location	FS (ft)	July 10-16	July 26-Aug.1 (crest stages in feet)	Sept. 23-Oct.1
St. Joseph	17.0	25.6	32.7	20.2
Kansas City	32.0	39.7	48.9	30.5
Waverly	20.0	29.1	31.2	24.8
Glasgow	25.0	37.1	39.8	30.0
Boonville	21.0	34.3	37.1	29.7
Jefferson City	23.0	34.7	38.6	31.0
Hermann	21.0	34.9	36.3	31.9
St. Charles	25.0	36.7	39.5	35.2

6. JULY 26 - AUGUST 1, 1993; RECORD FLOOD STAGES

With major flooding already occurring, additional heavy downpours in late July, concentrated in the quadstate area of northwest Missouri, northeast Kansas, southeast Nebraska, and southwest Iowa exacerbated conditions in the lower Missouri River Basin.

On July 26, a peak flow of approximately 410,000 cfs passed St. Joseph, Missouri, setting a new record stage of 32.69 ft. The previous flood of record, 26.82 ft. (397,000 cfs) occurred on April 22, 1952. Annual mean flow at this location is approximately 41,000 cubic feet per second (cfs) (Figure 3).

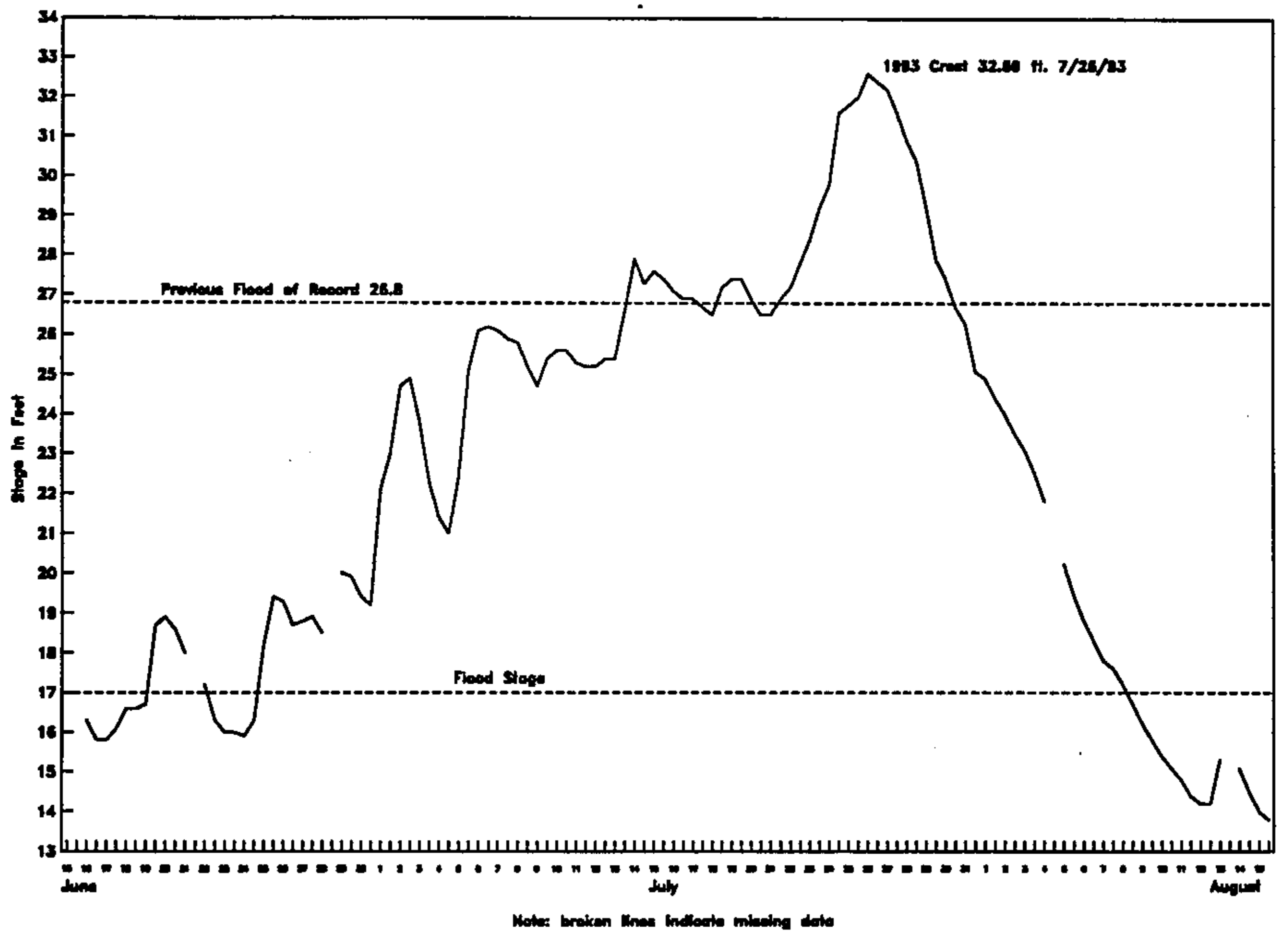


Figure 3. St. Joseph, Missouri record stages.

In late July, runoff plus a sustained release of approximately 100,000 cfs from Corps impoundments resulted in a peak flow of about 200,000 cfs in the Kansas River at its confluence with the Missouri River at Kansas City, Missouri.

At Kansas City, Missouri the peak routed flow from St. Joseph nearly coincided with that from the Kansas River, resulting in an estimated peak discharge between 600-625 thousand cfs (including local runoff contributions between St. Joseph and Kansas City). Sustained routed flows kept the stage at Kansas City near its crest of 48.9 ft. for two days (July 27-28) (Figure 4). Records show that the flood of June 16, 1844, peak discharge was 625,000 cfs, as computed by the US Army Corps of Engineers. For the period of gauged records beginning October 1897, peak discharge was 573,000 cfs on July 14, 1951. Annual mean flow past Kansas City, Missouri, is approximately 50,000 cfs.

The following is a summary of hydrologic events at each forecast point as the flood wave progressed downstream to St. Charles, Missouri.

Waverly, Missouri: River mile 293.4-breached and overtopped levees in this reach of the Missouri River allowed floodwater to cover the approximately 8

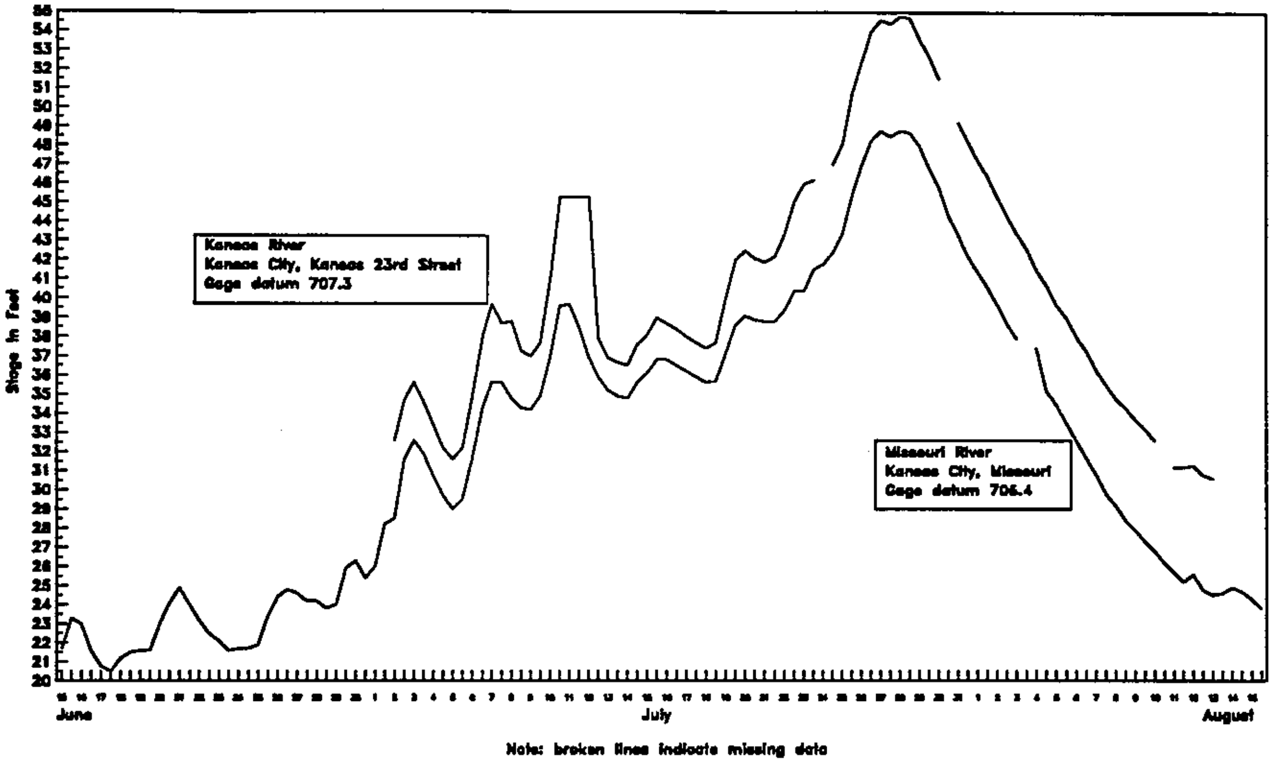


Figure 4. Missouri and Kansas Rivers stages.

to 9 mile wide floodplain. Upstream flow impulses were attenuated here as the vast amount of storage in this reach served as a flow regulating reservoir; stages were near crest (31.2 ft on July 28) for 72 hours; the sustained draft (outflow) from this point is estimated between 575 and 600 thousand cfs for 3 days. Previous record discharge was 549,000 cfs on July 16, 1951. Annual mean flow at Waverly is approximately 51,000 cfs.

Between Kansas City and Waverly, the Missouri River had cut through its bank and levees, and traversed several miles, covering roads and farmlands in late July; the COE reported forty-four other "washouts" at various locations along the river.

Glasgow, Missouri: River mile 226.8-peak flow contributions from the Grand River (100 to 125 thousand cfs est.) and Chariton River above Glasgow combined with the sustained discharge from Waverly. The Grand River at Chillicothe, Missouri crested on July 27, and the Chariton River at Novinger, Missouri, crested on July 28.

Near Glasgow, earlier in the month around July 14, the Missouri River cut through a levee and railroad embankment and started a new channel. Post flood reconstruction of this section of riverbank involved, in part, pumping river sand to fill in a 2000 ft long, 80 ft deep hole.

A section of the Gateway Western rail trestle collapsed on July 29 and floodwater also damaged the bridge for State Highway 240. The USGS automatic gauge, on Highway 240 bridge was also damaged; subsequently COE personnel relayed manual stage readings at Glasgow to the RFC.

Peak flow at Glasgow, Missouri was approximately 675 to 700 thousand cfs (crest stage 39.6 ft) on July 29, 1993. An examination the Glasgow hydrograph shows a marked increase in the rate of rise from mid-morning on July 28 to around 7:00 am CDT on July 29 before cresting around 6:00 pm CDT, which is the effect of the routed hydrographs from the Grand and Chariton rivers. Below Glasgow, less overbank storage was available for attenuation of the flood peak.

Boonville, Missouri: River mile 197.1-the flood plain width at this forecast point is approximately two miles, similar to that of the next downstream point, Jefferson City; these locations have relatively narrow floodplains compared to Waverly or Glasgow. Peak flow is estimated at 700 thousand cfs; the USGS measured discharge was 698,000 cfs on July 30, 1993. Flood crest was approximately 37.1 ft on July 29 and July 30. Records indicate a peak flow of 710,000 cfs as computed by the U.S. Army COE, on June 21, 1844. During the 1951 flood, a discharge of 550,000 CFS was recorded on July 17. Annual mean flow at Boonville is approximately 61,000 cfs.

Jefferson City, Missouri: River mile 143.9-the Missouri River crested at 38.6 ft on July 30, 1993; peak flow between 700 and 725 thousand cfs. The automatic gage failed near the crest period, and the COE relayed manual stage readings to the RFC.

A high water mark of 38 ft. from the 1844 flood was exceeded by the crest stage of the late July 1993 event; however, the 19th Century high water mark is disputed by some historians. (The flood of June 1844 is considered the greatest known event in the lower Missouri Basin)

Hermann, Missouri: River mile 97.9-the Missouri River crested at 36.3 ft. on July 31, 1993, Figure 5, peak flow was between 725 and 750 thousand cfs. Releases from Bagnell Dam (Lake of the Ozarks) were only about 1000 cfs during this period and most of the Osage River was in backwater condition from the Missouri River. For the flood of June 1844, peak discharge computed by the U.S. COE, was approximately 892,000 cfs. In 1903, a discharge of 676,000 cfs was measured on June 6. The discharge for the 1951 flood was 615,000 cfs on July 19. Annual mean discharge at Hermann is approximately 77,000 cfs.

The distance between Hermann and Kansas City gauge locations is 268.2 river miles. The flood wave traveled this distance in approximately 63 hours. The celerity of the flood wave was between 4 and 4.5 mph or in the range of 6 to 6.5 feet per second. The average velocity in the river was between 4 and 4.5 feet per second. Of course, velocities in the main channel were much higher, especially through bridge crossings, while velocities in overbank areas approached negligible values.

St. Charles, Missouri: River mile 28.2-crested at 39.5 ft (approx.) on August 1, 1993; several levees failed in the vicinity of the automatic gauge, disrupting the performance of the device at a critical time near the crest. Wire weight stage readings taken by the USGS were relayed to the MBRFC by the U.S. Army Corps of Engineers.

Crests along the Missouri River, as the flood wave moved from Boonville to St. Charles, indicated less attenuation than expected. Rainfall from July 28-August 1 was not significant, and it was thought that during this time, enough water would move out of overbank areas leaving storage available for greater attenuation of the flood wave; however, this did not occur, as valley storage was still nearly exploited.

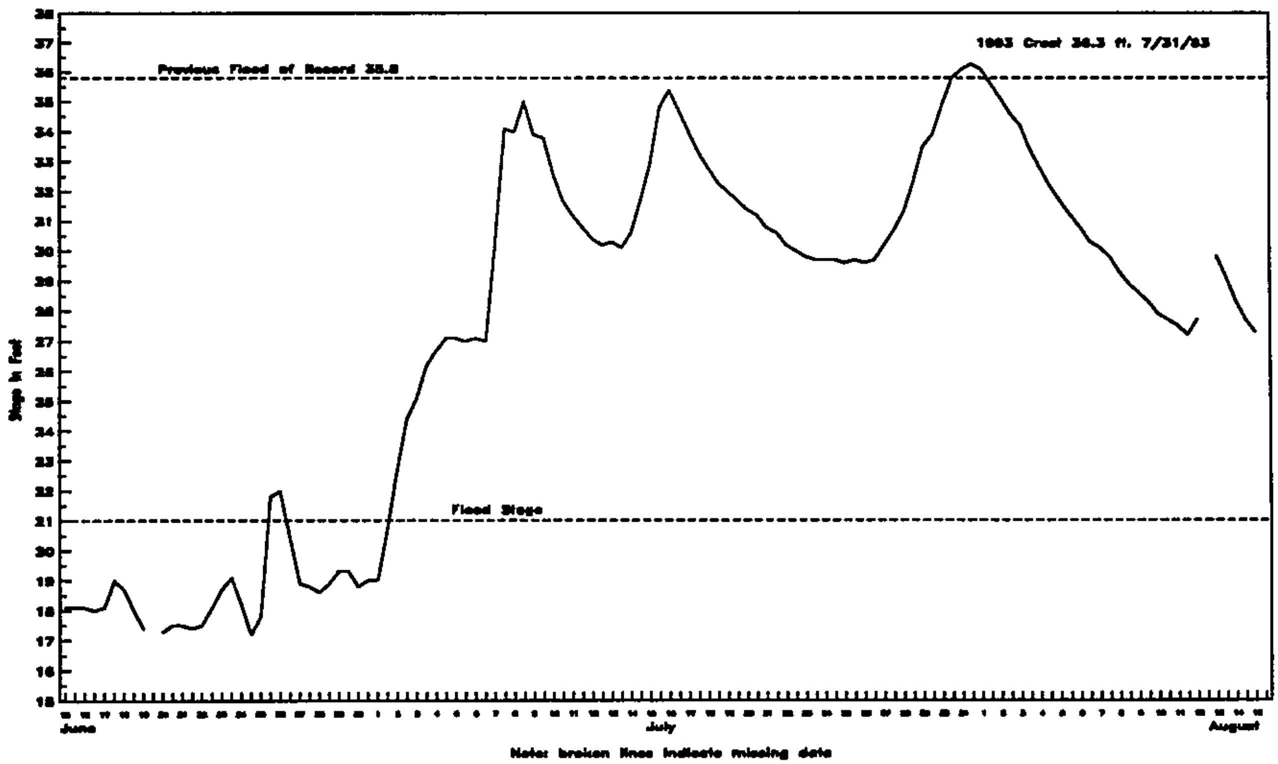


Figure 5. Hermann, Missouri flood stages.

The contribution of the Missouri River was approximately two-thirds of the total flow of the Mississippi River per measurements taken at St. Louis by the USGS in late July-early August. Latest available USGS measured discharges are 758,000 cfs at Hermann, Missouri on July 31, 1993, and approximately 1.1 million cfs at St. Louis on August 1, 1993.

7. HYDROLOGIC FORECASTING METHODOLOGY

Hydrologic forecasting at the MBRFC requires the use of several computer models to simulate the rainfall-runoff process and route computed hydrographs downstream. An array of communications hardware and software is also needed to receive and send data, transmit forecast products, messages and other information.

Two mainstay computer programs are the soil moisture (API) and flow (RIVALL) models; an abbreviated description of the hydrologic forecasting process and the role of these models follows.

Data (precipitation, reservoir releases, river stages, etc.) received from NWS offices, the COE, paid and volunteer observers, etc. are decoded at the RFC. River Forecast Center hydrologists review the data for quality control purposes. Mean areal precipitation values are computed either manually or via computer. Heavy convective-type precipitation concentrated locally necessitates manual determination of mean areal precipitation (MAP) for a particular runoff zone. MAP computations via computer usually suffice for the more uniform and widespread stratiform-type precipitation.

The antecedent precipitation index (API) procedure, a summation of prior precipitation amounts weighted according to time of occurrence, indicates initial soil moisture conditions at the onset of a storm event. The time of year (represented by week number) influences antecedent basin conditions; relationships for each week of the year have been developed to disaggregate rainfall over an area into runoff and recharge. Storm rainfall is converted to runoff via a single family of curves. Relationships between precipitation, soil moisture and runoff are defined using a coaxial multi-variable correlation. A graphical depiction of the coaxial rainfall-runoff relationship is provided in most hydrology texts. Finally, the RIVALL model applies computed excess precipitation for each runoff zone to a unit hydrograph. There are more than 700 runoff zones in the Missouri River basin.

Presently, MBRFC does not directly use NWS forecast precipitation as part of daily operations. The future or forecast precipitation product, Quantitative Precipitation Forecast (QPF), is developed at the National Meteorological Center (NMC) in Suitland, Maryland. WSFOs refine QPF for their local areas. During the 1993 summer floods, various contingency river model runs for certain drainage areas were made using QPF for the U.S. Army Corps of Engineers to provide inflow scenarios for COE impoundments, and to assist their decision making process regarding reservoir release schedules.

Discharge hydrographs are routed downstream using either the Lag & K or Tatum or Muskingum method. The Tatum method is used for routing flows in the lower Missouri River. Finally, discharge hydrographs are converted to stage hydrographs using rating curves. Most ratings were developed by the USGS or COE.

Refinements to hydrologic programs are often required as lumped parameter models are used to represent complex physical processes having behavioral variations. The staff of hydrologists at the Missouri Basin RFC continually update models by recalibrating parameters, as needed. Of course, historical data over a sufficient period of record must be available for calibration.

The relatively simplistic hydrologic models used at the Missouri River Basin RFC work remarkably well, provided model parameters are periodically calibrated. During the 1993 summer flooding in the Missouri River basin, complicating factors such as heavy convective downpours over isolated areas, levee failures, and flood crests that exceeded historical records; ran afoul of the RFC models' capabilities, and challenged the expertise and judgement of forecasters.

8. FORECASTING DIFFICULTIES

During the summer floods of 1993, numerous phenomena could not be simulated by the river forecasting model (RIVALL). Limitations of the river mechanics component of the model and the resultant uncertainty among forecasters created some anxious moments. The gap between actual and simulated conditions along the Missouri River widened when information (data) was not forthcoming. The bases for the majority of hydrologic forecasting difficulties are discussed.

(a) The magnitude of flooding often exceeded the limits of stage-discharge ratings used in the RIVALL model (Table 3). Loop ratings, which account for the influence of changing friction slope during the progress of a flood, were not available for the mainstem of the Missouri River.

Rating curves or tables relate (measured) flows to (observed) stages at a particular location. A singular or unique rating at each forecast point is a best fit curve through a collection of stage-discharge points. Loop ratings are applicable for the nonuniform and unsteady flow conditions during flooding because discharge is not a function of depth alone. However, had loop ratings, or crest-stage relationships at forecast points been constructed based on the 1951 flood (the last event of similar extent and magnitude) data, then levee construction since that time would have negated their validity. Further complicating matters, levee overtopping and failures in 1993 upset storage routing computations. Therefore, at several forecast points, incorrect computed flows would not have yielded reliable stages had loop ratings been available.

(b) Backwater effect due to bridge crossings, etc. could not be simulated by the hydrologic model (RIVALL) used by hydrologists at the RFC. However, the hydraulic resistance or roughness in overbank areas influenced river levels to a greater extent than bridge piers. Nevertheless, energy losses from structures, changes in cross sections, and friction were not computed. River stage readings taken from the downstream side of bridges, where the water surface level was influenced by the expansion of flow passing through the bridge piers, may have been low due to the drawdown effect compared to stages obtained from ratings.

TABLE 3

MISSOURI RIVER
DAILY FORECAST POINTS IN MISSOURI

LOCATION	LIMIT OF RATING		1993 FLOOD CREST	
	Stage (ft.)	Flow (1000 cfs)	Stage (ft.)	Flow (1000 cfs)
St. Joseph	31.0	366.0	32.7	410.0
Kansas City	46.6	540.9	48.9	615.0
Waverly	30.0	284.0	31.2	600.0
Glasgow	37.0	377.0	39.6	700.0
Boonville	33.0	381.0	37.1	725.0
Jefferson City	35.0	420.0	38.6	725.0
Hermann	36.0	566.0	36.3	750.0
St. Charles	39.0	565.0	39.5	-

River and stream junctions also created backwater conditions. Some graphical backwater relationships were available for tributaries of the Missouri, but none for the mainstem itself. Floodwater stored in tributaries did have a significant impact on routings. Routing difficulties are addressed in the next subsection.

Following are just a few of the many backwater conditions prevalent during the 1993 flood in the lower Missouri Basin.

At the Renz Correctional facility near Jefferson City, Missouri, workers unsuccessfully sandbagged Turkey Creek in an attempt to stop Missouri River backwater. Eventually, failed levees and sandbag walls left the site inundated.

The Grand and Osage rivers, numerous small creeks and streams were in backwater from the Missouri River.

Backwater from the Mississippi River extended (at least) to the St. Charles, Missouri, gauge location on the Missouri River.

(c) Failure of federal and nonfederal levees limited the usefulness of hydrologic routing algorithms in the forecast model (RIVALL), as floodwaters moved in and out of valley storage.

The Tatum or Successive Average-Lag method of routing is used for virtually the entire Missouri River. This technique can be generally described as time displacement of average inflow (to a river reach); routing constants vary as to the number of routing steps in a reach. However, routing constants used in the RIVALL model had never been calibrated for flooding of this magnitude. Variations in storage conditions within each subreach due to levee failures and overtopping altered the translation time of the flood wave upon which the number of routing steps in a reach were predicated.

RIVALL computed flows exceeded USGS field measurements in the first half of July; by late July, cascading errors from the hydrologic routing methodology resulted in computed discharges 15 to 20 percent less than USGS flow measurements along the lower Missouri River.

(d) Scour or deposition occurring in a river channel changes the base ratings. The RIVALL model allows for shifting stage-discharge ratings negatively or positively. Rating adjustments per latest available USGS discharge measurements were implemented as required at forecast points.

(e) Automatic gage problems and failures, often at critical periods near crest stages, were a major source of consternation for MBRFC hydrologists. Both manual (wire weight or staff) and automatic gage readings were taken along the Missouri River. The gage to river-mile ratio varied from about 1/30 to 1/50 during the flood due to gage-related problems.

Until late July, 1993, Missouri River stage forecasts were generally very good. However, forecasts at St. Charles were occasionally unreliable due to backwater effects from the high level of the Mississippi River. Table 4 lists the Missouri River daily forecast points in the state of Missouri and Figure 6 is an example of the daily river forecast product issued by the MBRFC.

The RIVALL model used a straight line extrapolation of the stage-discharge rating whenever computed flows exceeded the upper limit of the rating for a particular forecast point. Unfortunately, this extrapolation procedure yielded forecast stages that were too high. In reality, the slope of a rating curve would decrease as floodwaters overtopped levees, or otherwise moved into overbank areas. Estimated stage hydrographs were sketched under the computed ones, but computed flows were allowed to be routed downstream. Stage forecasts were made from the sketched hydrograph.

The tedious and time consuming procedure of manually drawing estimated hydrographs worked satisfactorily for a time; however, the volume of water under the recession limbs of some hydrographs needed to be increased to account for storage in overbank areas. The blend period (time over which errors between computed and observed values are minimized by the RIVALL model) was lengthened on July 21, prior to the record flood episode of July 27 to August 1. Despite these efforts, water accounting fell short compared to late July flow measurements taken by the United States Geological Survey (USGS).

TABLE 4

MISSOURI RIVER BASIN

DAILY FORECAST POINTS IN MISSOURI[2]

LOCATION	RIVER MILE	DRAINAGE AREA (sq.mi.)
St. Joseph	448.2	424,340
Kansas City	366.1	489,162
Waverly	293.4	491,230
Glasgow	226.3	502,875
Boonville	197.1	505,710
Jefferson City	143.9	507,525
Hermann	97.9	528,200
St. Charles	28.2	529,190

Regarding levee failures, floodwater pouring through the breach would quickly fill the available storage areas. The progression of the water would usually be halted by backup (diversion) levees, high ground or eventually the valley wall. In many locations, the floodwaters covered the entire river valley and the river literally extended bluff-to-bluff. The movement of floodwater into overbank areas (and human efforts to impede the march of the flood) was dynamic in nature; therefore, the stage-discharge relationship at a particular location would change as the cross section changed.

Temporal and spatial variations of the flood wave, for which routing algorithms could not fully account, were due mainly to levee failures. The movement of floodwater into, out of, and through overbank areas could only be simulated indirectly. A few examples of possible water movement in the floodplain follow.

[2]During the 1993 summer floods there were twelve (12) daily forecast points and nine (9) flood only forecast points along the lower Missouri River (below Gavin's Point dam in South Dakota).

MKCRVFMOM
ETTAAOO KKRF 231725

MISSOURI RIVER STAGES FORECASTS
NATIONAL WEATHER SERVICE
FRI JUL 23 1993

STREAM/STATION	FS	TODAY	7/24	7/25	7/26	CREST/DATE
MISSOURI RIVER						
SO SIOUX CITY NE	30	21.1	20.3	19.7	19.0	CONT TO FALL
DECATUR NE	35	27.2	CONT TO FALL			
BLAIR NE	29	23.6	CONT TO FALL			
OMAHA, NE	29	27.2	26.8	26.3	25.8	SLW FALL EXP
NEBRASKA CITY NE	18	24.3	25.5	25.5	25.1	25.5-26.0 7/23PM
BROWNVILLE NE	32	40.8	NR 42.3 FT 7/23 EVE			
RULO NE	17	23.7	24.2	24.2	23.8	NR 243.3 7/23PM OR 7/24AM
ST JOSEPH MO	17	28.4	29.7	29.6	29.4	NR 30.0 7/24
ATCHISON KS	22	E27.2	NR 28.0 FT 7/24 PM			
KANSAS CITY MO	32	E41.2	42.3	43.4	43.4	43.5-44.0 7/25
SIBLEY MO	22	E30.5	BETW 32.0-32.5 FT 7/26 AM			
NAPOLEON MO	17	E25.5	BETW 27.5-28.0 FT 7/26 AM			
WAVERLY MO	20	29.1	30.2	31.8	32.9	33.0-33.5 7/27
MIAMI MO	18	E30.4	NR 33.5 FT 7/27PM OR 7/28AM			
GLASGOW MO	25	*33.1	34.0	35.0	36.7	39.0-40.0 7/28
BOONVILLE MO	21	30.9	31.8	32.7	33.8	36.0-37.0 7/28 PM
JEFFERSON CITY MO	23	31.6	32.1	32.8	33.6	37.0-38.0 7/29
GASCONADE MO	22	*33.0	BETW 35.0-35.5 7/29PM OR 7/30 AM			
HERMANN MO	21	29.8	30.0	30.6	NR 34.5 7/29 OR 7/30	
ST CHARLES MO	25	34.7	34.5	34.5	34.6	36.5-37.0 7/30 OR 7/31

Figure 6. Daily river forecast product issued by the MBRFC.

(a) If levees were overtopped but not breached, floodwater could be trapped on the backside of levees and not return directly to the river.

(b) As the river level receded, water in overbank areas moving back through levee breaches would be ponded in borrow areas or trapped in epressions and scoured-out areas.

(c) Losses of flow at riverbank washouts (e.g. near Orrick and Glasgow, Missouri) where the Missouri River cut new channels, went into permanent storage. Eventually floodwater evaporated from ponded areas or percolated into the soil.

Criticism of the river mechanics component of the NWS river forecasting model used by the Missouri Basin RFC was generally based on the model's inability to handle the full range of flow conditions that occurred. However, much of this criticism is unfounded. In many places, flooding far exceeded historical levels and those record events from which data was used to develop rating curves and calibrate routing parameters. Further, the exact sequence of levee failures could not have been predicted by any computer model.

Some members of the academic community, quoted in the media, could not understand why a more physically-based, distributed parameter flow model is not used operationally. Hydraulic routing employing the equations of a full dynamic wave (Saint-Venant equations for unsteady flow) requires description of initial and boundary conditions at each cross section. Given the aforementioned levee failures, riverbank washouts, channel scour and deposition, sandbagging efforts, damages to bridges, etc., cross sections were constantly changing. Many hydraulic models linearly interpolate between cross sections in order to define points along the river; however, in 1993 along the Missouri River, levee failures (and therefore routing losses) occurred between stations having known cross sections.

In the hydraulic model described above, differential equations for conservation of mass and momentum, written in finite difference form, are solved by either an explicit or implicit finite difference method. Each method has its limitations, and a detailed description of numerical methods is beyond the scope of this paper. Suffice to say that finite difference methods can exhibit instability if the global rounding error is not limited (calculations are performed to a finite number of decimal places or significant figures which introduces an error). Discretization errors also affect convergence of the exact solution of the approximating finite difference equations to the solution of the differential equations.

It should be noted that NWS in-house expertise in hydraulic modeling has been available for many years. Dam failure (DAMBRK) and hydraulic routing (DWOPER) programs developed by D.L. Fread are internationally recognized. These computer programs are used more in an analysis mode than for real-time flood forecasting. If cross sections in a river system remained constant, then a hydraulic model would have utility; however, the river forecasting process would become too unwieldy if constant adjustments to input data and hydraulic algorithms were required. The limited time in which RFC hydrologists must analyze data, make model runs, and issue forecasts would not allow time for constant adjustments of a physically-based hydraulic flow model. A physically-based hydraulic model would not have been the panacea suggested by some.

9. SUMMARY

In the wake of the 1993 Midwest flood, levees will be rebuilt, riverbanks will be reconstructed, and flood survivors will try to rebuild their lives.

The Corps has already repaired some of the banks and levees along the Missouri River; however, much more work needs to be done if the river valley is to be restored to pre-flood condition. Floodplain regulations will be scrutinized (as they are after every flood); however, many people have already decided to relocate their residences and businesses out of the floodplain. Neither the National Weather Service nor the Missouri Basin RFC have any input concerning land use decisions. A discussion of land use policy or development in floodplains is beyond the scope of this paper.

Three basic philosophies have emerged in the aftermath of the flood.

(a) Environmentalists prefer not to have all of the damaged levee systems repaired; rather they want some overbank areas left as wetlands and wildlife preserves.

(b) Others want all levees rebuilt as soon as possible so that commercial, agriculture, and transportation interests can resume.

(c) Some suggest conducting a study of the entire basin to ascertain flood control alternatives and how to better manage the river.

Each of the above ideas has certain merits. Hopefully, local, state, and federal officials will work out a compromise. The Missouri Basin RFC will need to be informed of post flood reconstruction along the Missouri River and its tributaries so that adjustments can be made to stage-discharge ratings and routing parameters in the forecasting model. Eventually, the USGS will recompute all ratings at (USGS) stations.

10. CONCLUSIONS

The purpose of this paper is to relate experiences at the Missouri Basin River Forecast Center during the spring and summer flooding of 1993. Peak flow and record stage values presented herein are subject to change; the United States Geological Survey will make the final determination on these values and publish their findings in the appropriate water supply papers.

The record-breaking floods of 1993 were the result of meteorological anomalies, but hydrologic anomalies also occurred. For example, in late July, peak flows in the Kansas and Missouri Rivers coincided at Kansas City, where, thankfully, the levees held. Synchronization of flood crests continued at confluences with the Grand and Mississippi rivers. Protracted stage levels so near crest, allowed for the virtual, if not exact, coincidence of peak flows.

11. NATIONAL WEATHER SERVICE MODERNIZATION

The National Weather Service is in the midst of a modernization program that promises to greatly improve forecast and warning capabilities. The scope of this program is enormous; therefore, only briefly mentioned are some of the new technologies.

New software will provide interactive river forecasting capability at RFC's. Hydrologic models will be executed on local workstations in less time than currently needed. Presently, model runs are submitted in batch fashion to a central computer; lengthy turn-around times are not unusual when many jobs are stacked in the queue.

Other NWS improvements include doppler radars (WSR-88D), automated surface observing systems (ASOS), new geostationary satellites, and advanced data processing and communication systems. The array of advanced technologies implemented over the next several years will provide and process tremendous amounts of hydrologic and hydrometeorologic data.

NWS hydrologists will be trained extensively in the use of many of the new technologies; however, technological improvements will not eliminate the need for examination and interpretation of data by hydrologists. Professional experience and judgement in river forecasting are vital when interruptions and voids in the flow of information occur, especially during extreme flooding.

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